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Since mid-1984, the Defense Mapping Agency (DMA) has been computing predictions of pole position (x and y) and time difference (UT1-UTC = ΔUT) to support the NAVSTAR/GPS orbit determination process. These predictions are based upon the "derived Earth orientation parameters" published in the U. S. Naval Observatory's Earth Orientation Bulletin (Series 7) and are obtained by fitting these data to a set of models specified in the DMA/GPS Interface Control Document.

This paper presents a review of the models and processes by which the Earth orientation predictions are computed at DMA. The results of a study to assess the accuracy of these predictions are also presented. Finally, several proposed methods for improving the prediction accuracies without altering the basic models are discussed and evaluated.

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THE DMA/GPS EARTH ORIENTATION PREDICTION SERVICE

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SUMMARY

Since mid-1984, the Defense Mapping Agency (DMA) has been computing predictions of pole position (x and y) and time difference (UT1-UTC = ΔUT) to support the Navstar/GPS orbit determination process. These predictions are based upon the "derived Earth orientation parameters" published in the U.S. Naval Observatory's Earth Orientation Bulletin (Series 7) and are obtained by fitting these data to a set of models specified in the DMA/GPS Interface Control Document.

This paper presents a review of the models and processes by which the Earth orientation predictions are computed at DMA. The results of a study to assess the accuracy of these predictions are also presented. Finally, several proposed methods for improving the prediction accuracies without altering the basic models are discussed and evaluated.

1.0 INTRODUCTION

The GPS Master Control Station (MCS) has, as one of its primary functions, the requirement to provide the GPS satellites with ephemeris and clock information that can be transmitted to users in the navigation message. Tracking data collected by five monitor stations (MSs) are sent to the MCS and used, in combination with reference trajectories, to compute estimates and make predictions of ephemeris and clock states for the satellites [1]. These ephemeris and clock computations require the ability to transform between an Earth-fixed reference system and a basic inertial system. Completion of this transformation requires estimates of the Earth orientation parameters (EOP).

The EOP consist of the polar coordinates (x and y) and the time difference UT1-UTC. The polar coordinates represent the position of the true celestial pole with respect to a reference point fixed to the crust of the Earth (the Conventional International Origin, or CIO pole). The x coordinate is positive in the direction of Greenwich and the y coordinate is positive towards the west [2]. UT1-UTC (ΔUT) represents the difference between the rotational time scale, UT1, and the uniform time scale, UTC (Coordinated Universal Time). It can be applied to UTC to recover time based on the true rotational rate of the Earth (UT1). Prediction of the EOP must be based on extrapolation of observations.

The Defense Mapping Agency (DMA) is required to supply predictions of the EOP to

the MCS based on a model and in a format specified in an Interface Control Document (ICD-GPS-211) [3]. This requirement is satisfied through the use of an Earth orientation parameters prediction computer program (EOPP), which is run weekly at DMA. This program has been providing predictions of the EOP to the MCS since mid-1984. Section 2 of this paper presents a review of the data, models, and processing scenario used by DMA to produce the EOP predictions. Section 3 gives a summary of the accuracy of these predictions from the time the service started in mid-1984 to the end of 1985. A discussion and evaluation of methods which have the potential to improve the prediction accuracies are provided in Section 4. Finally, Section 5 presents conclusions which have resulted from this study.

2.0 DATA PROCESSING

2.1 EARTH ORIENTATION DATA

The Earth orientation data used for prediction of the EOP are provided by the U.S. Naval Observatory (USNO). These data primarily consist of those values of x, y, and ΔUT published under the heading of "derived Earth orientation parameters" in the weekly Earth Orientation Bulletin (U.S. Naval Observatory Time Service Publication - Series 7). These values are based on observations obtained solely from institutions within the United States [4].

In order to ensure the shortest possible delay between observation and data dissemination, USNO supplies DMA with the most recent EOP values prior to publication of the Series 7 Bulletin. These values are based on the USNO "quick CORE" solution and are available on the General Electric (GE) Mark III communications network through the USNO Rapid Data Service. The "quick CORE" pole values are determined primarily from satellite laser ranging (SLR) to the LAGEOS satellite. The ΔUT values from "quick CORE" are a combination of connected-element interferometer (CEI) observations, SLR, and optical observations [5]. In late 1985, the minimum delay between observation and availability was approximately one week.

After publication of the Series 7 Bulletin, the "quick CORE" EOP values in the DMA data base are replaced by the published values. These values result from USNO "regular CORE" solutions. The "regular CORE" pole values are based primarily on SLR observations and Doppler tracking of the TRANSIT navigation satellites. The "regular CORE" ΔUT values are based on a combination of CEI, SLR, optical, and Doppler observations [5]. Additional information concerning the USNO "CORE" solutions may be found in reference [6].

2.2 MODELS

2.2.1 POLE POSITION

The following models are used for the pole coordinates x and y [3]:

$$x(t) = A + B(t-t_a) + \Sigma C_j \sin[2\pi(t-t_a)/P_j] + \Sigma D_j \cos[2\pi(t-t_a)/P_j] \quad (1)$$

$$y(t) = E + F(t-t_a) + \Sigma G_k \sin[2\pi(t-t_a)/Q_k] + \Sigma H_k \cos[2\pi(t-t_a)/Q_k] \quad (2)$$

where: t_a = modified Julian date (MJD) of the first day of data

P_1, Q_1 = fixed Chandler period = 435.0 days

P_2, Q_2 = fixed annual period = 365.25 days

j, k = summation indices = 1, 2

The coefficients A, C_j, D_j, E, G_k, and H_k (j, k = 1, 2) are determined by least-squares adjustment. In practice, the drift terms are omitted from the models so that the coefficients B and F are set equal to zero.

2.2.2 UT1-UTC

Similarly, the ΔUT model [3] is:

$$\Delta UT(t) = I + J(t-t_b) + \Sigma K_m \sin[2\pi(t-t_b)/R_m] + \Sigma L_m \cos[2\pi(t-t_b)/R_m] \quad (3)$$

where: t_b = MJD of 0 January of the current year

m = summation index = 1, 2, 3, 4

In practice, this model is utilized by rewriting the expression for ΔUT:

$$\Delta UT = UT1\text{-}UTC = (UT2\text{-}UTC) - (UT2\text{-}UT1) \quad (4)$$

The term UT2-UT1 represents the "seasonal variation" and is given by the conventional formula:

$$\begin{aligned} UT2\text{-}UT1 = {} & 0.022 \sin[2\pi(t-t_b)/R_3] - 0.012 \cos[2\pi(t-t_b)/R_3] \\ & - 0.006 \sin[2\pi(t-t_b)/R_4] + 0.007 \cos[2\pi(t-t_b)/R_4] \end{aligned} \quad (5)$$

where: R_3 = 365.25 days

R_4 = 182.625 days

The Bureau International de l' Heure (BIH) seasonal variation coefficients are used in this expression [7].

The term UT2-UTC represents the difference between UTC and the nearly uniform rotational time scale, UT2, and is modeled by:

$$UT2\text{-}UTC = I + J(t-t_b) \quad (6)$$

Hence, in equation (3), $K_3 = -0.022$, $K_4 = 0.006$, $L_3 = 0.012$, and $L_4 = -0.007$. All remaining K_k and L_k are set equal to zero and the periods R_1 and R_2 are not used. The coefficients I and J are determined by least-squares adjustment. Details of the processing scenario for ΔUT will be given in Section 2.3.

2.3 EOP PREDICTION SOFTWARE

Predictions of the EOP are made through the use of a FORTRAN computer program (EOPP). This program was designed and coded by Mr. Gregory Arnold of DMA in 1984, and revised by the author in late 1985. The program first extracts the most recent 435 days of pole position data and the most recent 32 days of ΔUT data from the data base. The 435 days of pole coordinates span (approximately) one Chandler period. The decision to use 32 days of ΔUT data for prediction purposes was based on a study performed at USNO [4]. This study indicated that the smallest root mean square prediction errors (compared to BIH data), using a model similar to the one described in Section 2.2.2, were achieved using 32 days of ΔUT data.

The EOPP program then performs an unweighted batch least-squares fit to the x data, using the model described in Section 2.2.1. Based on the results of this fit, the data are edited so that any point whose post-fit residual lies outside three standard deviations is tagged. The batch least-squares fit is repeated using the untagged data. A similar procedure is followed for the y data. Since 1 January 1986, a method of "bias adjustment" has been used to improve the accuracy of the pole position predictions. This technique, which will be discussed further in Section 4, involves the post-fit adjustment of the x and y model bias terms (A and E) by the value of the residual at the last untagged data point. This essentially forces the residual at the last data point to zero.

The reduction of the ΔUT data is slightly more complicated. First, the input ΔUT values are adjusted for the seasonal variation by application of equation (5). The resulting values represent UT2-UTC (see equation (4)). These values are then fit, by batch least-squares, to a straight line (see equation (6)). The values are then edited in the same manner as the pole data, and the fit repeated using the untagged values. The seasonal variations are subtracted from UT2-UTC to obtain estimates of ΔUT.

2.3.1 THE EOP PREDICTION RECORDS

The EOPP program produces, as output, a set of five card-image records containing all information necessary to perform the EOP predictions. The format of these records is specified in ICD-GPS-211 and is given in Table 1. In addition to the coefficients resulting from the least-squares adjustments ($A, C_1, C_2, D_1, D_2, E, G_1, G_2, H_1, H_2, I$, and J), the periods ($P_1, P_2, Q_1, Q_2, R_1, R_2, R_3$ and R_4), and epochs (t_a and t_b) are given. Record 5 also contains the offset between International Atomic Time (TAI) and UTC.

The EOP prediction records are supplied to the MCS on a magnetic tape and are also placed in a file on the GE Mark III network for immediate availability. In the near future, establishment of a direct data link between DMA and the MCS will enable DMA to pass the

EOP prediction records to the MCS in the most timely manner [3].

3.0 ACCURACY OF THE DMA EOP PREDICTIONS

3.1 PROCEDURE

Each time the EOPP program is executed, the newly-computed set of EOP prediction records is appended to a permanent data base. This data base was examined carefully, and a number of duplicate sets of prediction records were removed. A total of 72 sets of prediction records remained after this editing was completed. The first of these sets was produced in July 1984 and the last set used in this study was produced in December 1985. The values from each set of prediction records (see Section 2.3.1) were inserted into the models specified in Section 2.2 and 40-day predictions of the EOP were computed. In each case, the first day of prediction was the day immediately following the last day of data used to determine a particular set of prediction records. The predictions were computed in 5-day increments.

These predictions were directly compared with the actual values of the EOP determined by USNO and differences (in the sense, observation minus predicted value) were computed. After all 72 sets of prediction records were processed, root mean square (rms) prediction errors at each 5-day increment were computed.

3.2 ACCURACY OF POLE POSITION PREDICTIONS

Figure 1 presents a plot of the rms error in the pole position predictions as a function of the age of the prediction. It can be seen that the x component of the pole was predicted with an rms error that grew nearly linearly from approximately 0.013 arcsec 5 days after the last day of data, to approximately 0.027 arcsec 40 days after the last day of data. The rms prediction error in the y component of the pole grew from approximately 0.009 arcsec to 0.016 arcsec over the same prediction interval. Predictions based on all 72 sets of EOP prediction records described in Section 3.1 entered into the determination of these rms errors. Note that a prediction error of 0.03 arcsec is approximately equivalent to an error of 1 meter at the surface of the Earth.

3.3 ACCURACY OF THE ΔUT PREDICTIONS

Figure 2 is an analogous plot which gives the rms error in predicting ΔUT as a function of the age of the prediction. When the rms errors based upon all 72 sets of EOP prediction records were plotted, it was noticed that the prediction errors did not increase with time. A detailed examination of the individual values indicated that predictions based on the first 7 sets of EOP prediction records exhibited unusually large prediction errors (20-30 arcsec). These large prediction errors appear to be due to an incorrect treatment of

the seasonal variation terms (see Section 2.2.2) in the first 7 runs of the EOPP program. Thus, a more realistic assesment of the ΔUT prediction errors can be made by eliminating the first 7 sets of EOP prediction records and recomputing the rms errors based on the remaining 65 sets. These errors are also plotted in Figure 2. It can be seen that the rms prediction error grows from 2.4 msec 5 days after the last day of data to 7.5 msec 40 days after the last day of data. A prediction error of 2.2 msec is approximately equivalent to a prediction error of 1 meter at the surface of the Earth.

4.0 EVALUATION OF METHODS FOR IMPROVING PREDICTION ACCURACIES

4.1 OVERVIEW

A short study was undertaken to investigate several techniques with potential to improve the accuracy of the EOP predictions. It must be emphasized that any improvements to the EOP processing scenario must be consistent with the models and output specifications given in ICD-GPS-211 (see Sections 2.2 and 2.3.1). Given these restrictions, data weighting schemes were given the most attention.

The procedure for evaluating these potential improvements was as follows. First, 25 test data sets were created through extractions from the DMA data base (see Section 2.1). The first data set commenced on MJD 44413 (23 June 1980). The first day of data for each subsequent set was incremented by 30 days, so that the last data set began on MJD 45133 (13 June 1982). Each data set consisted of 435 days of EOP values. All 435 days of pole data and the last 32 days of ΔUT data were utilized throughout testing. Each of the 25 test data sets was processed by the "production" version of the EOPP program, prediction records were generated and evaluated, and rms prediction errors were computed based on the results of all 25 test runs.

After the addition of each potential improvement to the EOPP program, the 25 test runs were redone. Again, the EOPP prediction records were evaluated and rms prediction errors generated. These rms prediction errors (at 5-day intervals) were then subtracted from the analogous prediction errors computed using the "production" results. The differences between rms prediction errors are a measure of the improvement or degradation of the predictions resulting from the processing modification. Each potential processing improvement will be discussed separately.

4.1.1 BIAS ADJUSTMENT

After the completion of each EOPP test run, the post-fit residuals were examined. The value of the residual at the last untagged data point was added to the bias term (A, E, or I) of the particular model (see Section 2.2). This procedure forces the "new" residual of the

last data point to be zero. Thus, predictions based on the adjusted coefficients should begin unbiased. Based upon the favorable results of a previous study [8], this method has been routinely applied to the pole position prediction results since 1 January 1986 (see Section 2.3).

4.1.2 CONSTRAINED SOLUTION

A very large weight (10^6) was assigned to the last data point. This essentially constrained the least-squares solution, resulting in a very small residual at the last day of data. Again, predictions based on this solution should begin unbiased.

4.1.3 TIME-WEIGHTED SOLUTIONS

Three different weighting schemes, each a function of time, were investigated. The general approach involved applying a particular weighting function to the last 30 days of pole data and the last 14 days of ΔUT data. These numbers were chosen rather arbitrarily, based on an examination of production run post-fit residuals.

4.1.3.1 RAMP WEIGHTING FUNCTION

Weights for the affected EOP values were determined by a linear function of time. The weights were scaled so that the last data point received a weight of 10 (largest weight).

4.1.3.2 EXPONENTIAL WEIGHTING FUNCTION

Weights for the affected EOP values were computed using an exponential function of time. Again, weights were scaled so that the last data point received the largest weight (a value of 10).

4.1.3.3 STEP WEIGHTING FUNCTION

Weights for the affected EOP values were set equal to the same value (10).

4.2 RESULTS

4.2.1 X-COORDINATE OF THE POLE

Figure 3 presents the differences between the rms prediction errors obtained using the various processing modifications and the rms prediction errors obtained from the production results. Each processing modification yielded a overall improvement in the accuracy of the x-coordinate predictions. The bias adjustment and constrained solution methods yielded the largest improvements in prediction accuracy. Use of the exponential, step, and ramp weighting functions produced very similar improvements which were less than the improvements obtained through the use of the first two methods.

4.2.2 Y-COORDINATE OF THE POLE

Figure 4 presents a similar plot of the rms prediction error differences for the y-coordinate of the pole. Again, each processing modification resulted in an overall improvement in prediction accuracy. This improvement, however, was much smaller than

the improvement in prediction accuracy evident in the x-coordinate results. In general, the improvement in prediction accuracy was quite similar for all of the tested techniques.

4.2.3 ΔUT

Figure 5 provides the rms prediction error differences for ΔUT. It is evident that only the bias adjustment method resulted in an overall improvement in prediction accuracy. This improvement is quite small (at the half-msec level). Use of the remaining techniques resulted, generally, in no overall improvement in the ΔUT prediction accuracy.

5.0 SUMMARY OF RESULTS AND CONCLUSIONS

DMA has been supplying sets of EOP prediction records to the MCS on a weekly basis since mid-1984. These EOP prediction records are based on unweighted batch least-squares adjustments to the EOP data (x, y, and ΔUT) supplied by USNO. The accuracy of the EOP predictions can be assessed by comparing the predictions with the actual USNO EOP values available at a later time. This has been done for 72 sets of EOP prediction records produced from July 1984 to December 1985. The rms prediction errors for the x coordinate of the pole did not exceed 0.03 arcsec (approximately one meter on the surface of the Earth) over prediction intervals of 40 days. The rms prediction errors for the y coordinate of the pole did not exceed 0.02 arcsec over the same prediction interval. A processing error was discovered which adversely affected ΔUT predictions from the first 7 sets of EOP prediction records. When these 7 sets were omitted from analysis, the rms prediction errors for ΔUT were found to be less than 8 msec over the 40 day prediction interval.

Several techniques with potential for improving the accuracy of the EOP predictions were evaluated. These techniques included post-fit adjustment of the model bias terms, constraining the least-squares solution through the last data point, and three weighting functions (a ramp, an exponential, and a step function) applied to the last 30 days of pole values and the last 14 days of ΔUT data. Generally, all of these techniques improved the pole position prediction accuracies during the test period. The improvement ranged from approximately 0.010 arcsec to approximately 0.020 arcsec for the x component, depending upon technique and the prediction age. The improvement was less for the y component, ranging from approximately 0.002 arcsec to approximately 0.005 arcsec, again depending upon method and prediction age. However, only the bias adjustment technique improved the ΔUT predictions. This improvement was minimal. The remaining methods generally produced no improvement in prediction accuracy.

It is important to note that no attempt was made in this study to determine an optimal

technique or procedure for improving the EOP predictions. Certainly, other weighting functions and weight values could be tested. Experiments could be performed which vary the amount of data weighted. However, the results presented in this paper indicate that techniques which favor the last days of data lead to improved predictions of the pole coordinates when the models specified in Section 2.2.1 are utilized. These results also indicate that the same techniques applied to the ΔUT predictions are not likely to lead to improved predictions when the model specified in Section 2.2.2 is employed.

6.0 ACKNOWLEDGEMENTS

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TABLE 1: FORMAT OF THE EOP PREDICTION RECORDS

Record Number	Item Position	Format	Item Name
1	1	F10.2	t_a
	11	F10.6	A
	21	F10.6	B
	31	F10.6	C_1
	41	F10.6	C_2
	51	F10.6	D_1
	61	F10.6	D_2
	71	F6.2	P_1
	77	4X	Fill
2	1	F6.2	P_2
	7	F10.6	E
	17	F10.6	F
	27	F10.6	G_1
	37	F10.6	G_2
	47	F10.6	H_1
	57	F10.6	H_2
	67	F6.2	Q_1
	73	F6.2	Q_2
	79	2X	Fill
3	1	F10.2	t_b
	11	F10.6	I
	21	F10.6	J
	31	F10.6	K_1
	41	F10.6	K_2
	51	F10.6	K_3
	61	F10.6	K_4
	71	10X	Fill
4	1	F10.6	L_1
	11	F10.6	L_2
	21	F10.6	L_3
	31	F10.6	L_4
	41	F9.4	R_1
	50	F9.4	R_2
	59	F9.4	R_3
	68	F9.4	R_4
	77	4X	Fill
5	1	I4	TAI-UTC
	5	I5	Serial No.
	10	I6	Effectivity Date
	16	1X	Fill
	17	A18	Generation / Label Info
	35	46X	Fill

Figure 1: Prediction Accuracy – Pole Position
(72 Prediction Record Sets)

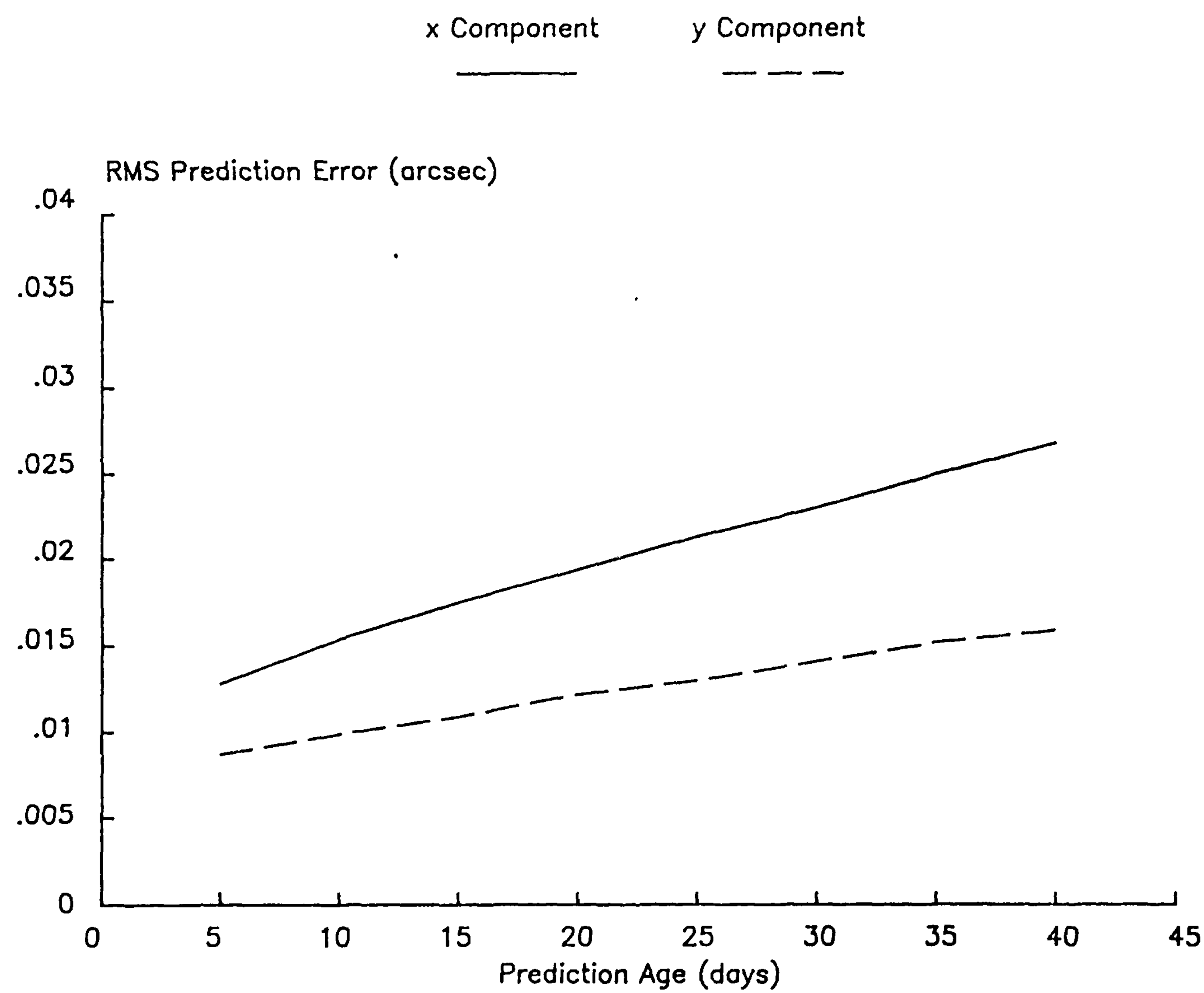

Figure 2: Prediction Accuracy — UT1–UTC

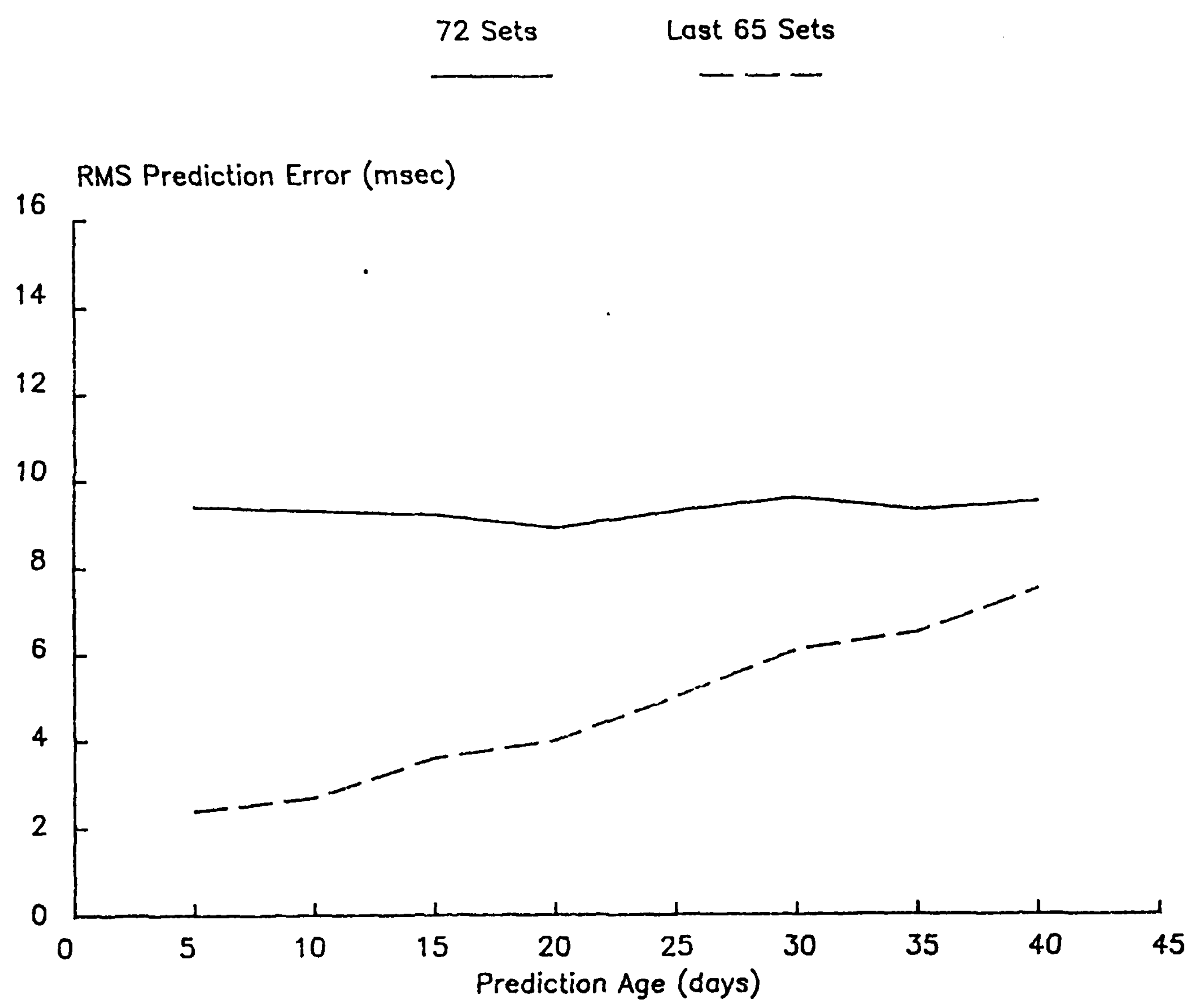

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Figure 3: Improvement in x Predictions
(compared with "production" solutions)

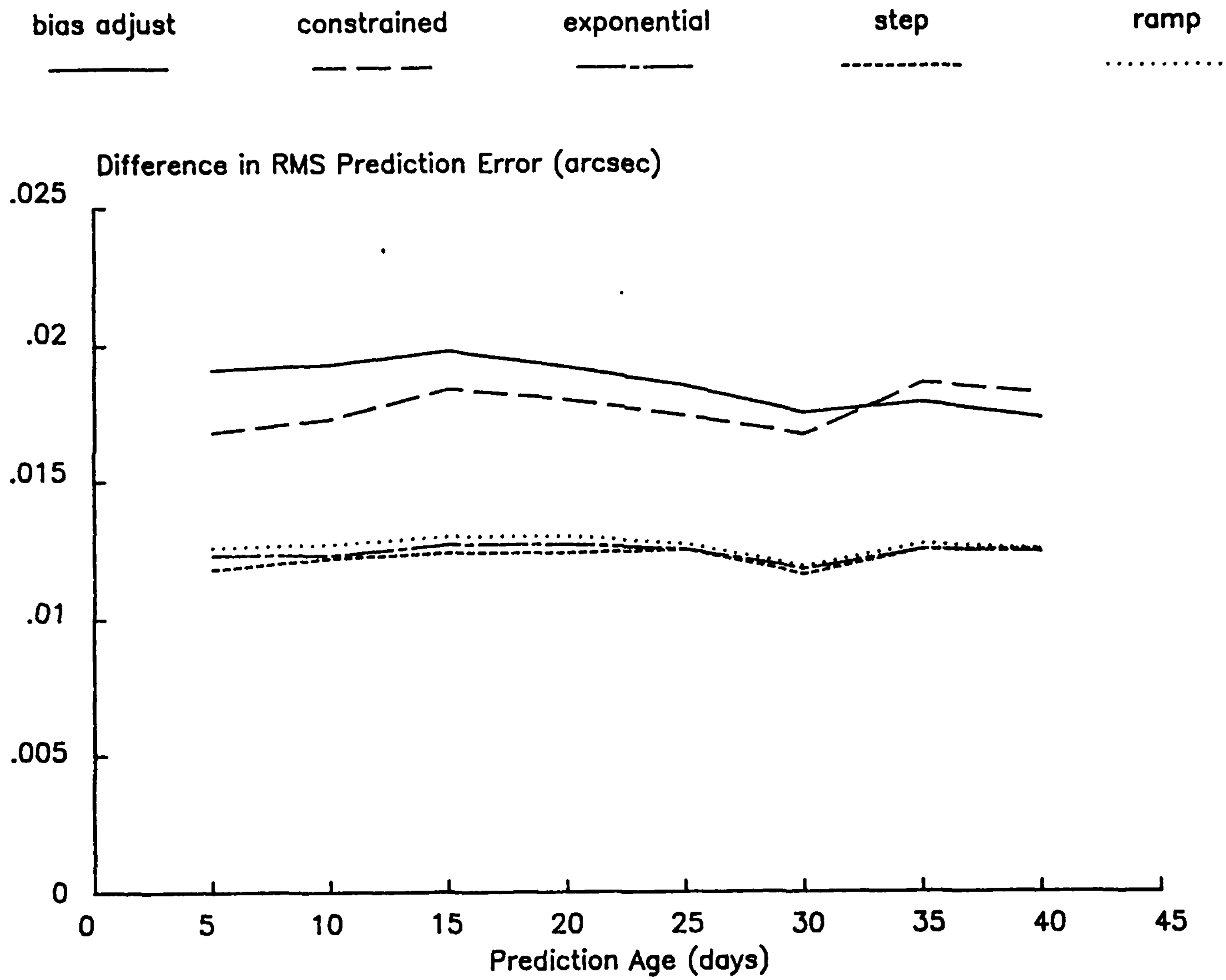

Figure 4: Improvement in y Predictions
(compared with "production" solutions)

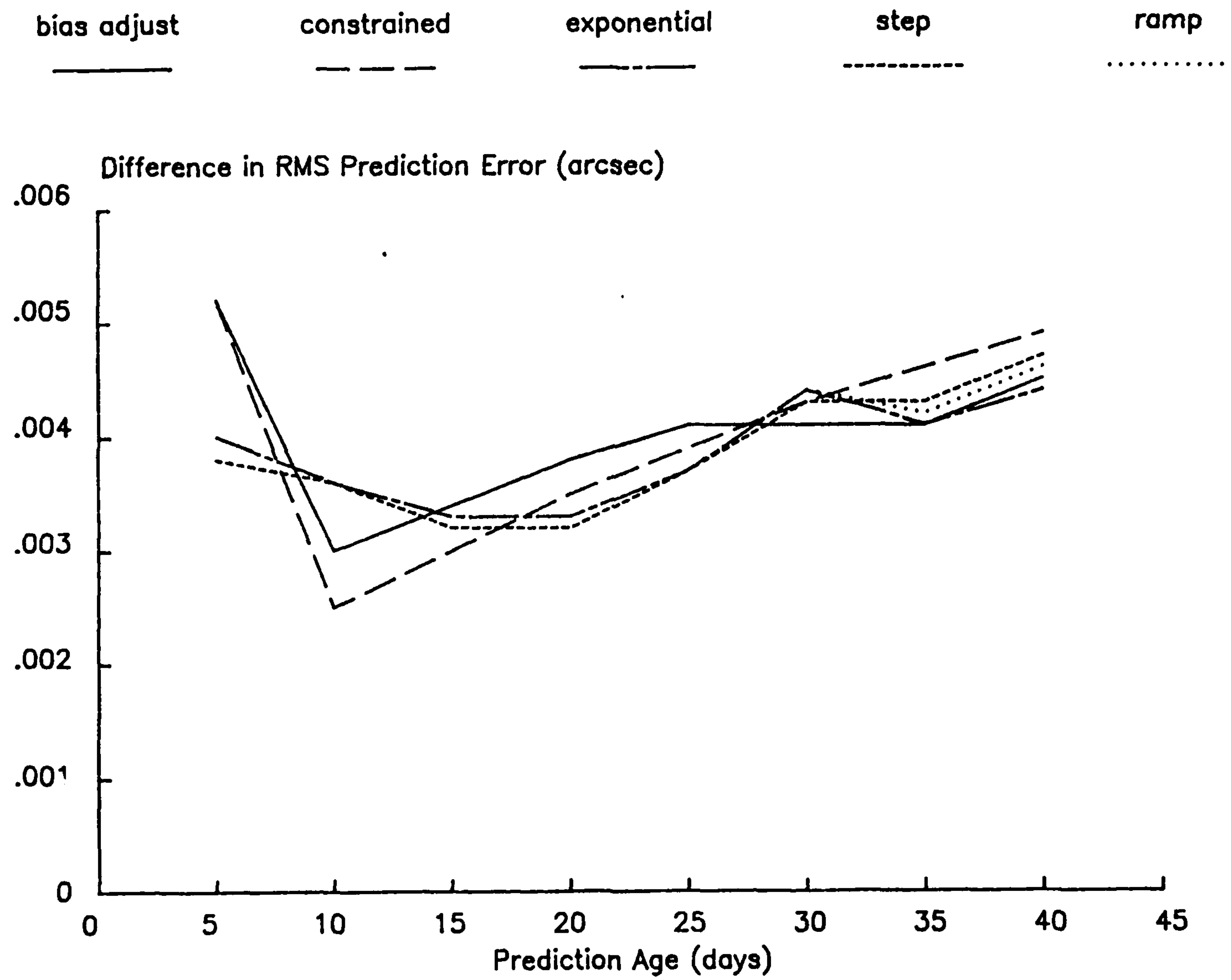

Figure 5: Change in UT1–UTC Predictions
(compared with "production" solutions)